The University of Chicago

STRUCTURAL PETROLOGY OF THE PINE CREEK AREA, DICKINSON COUNTY, MICHIGAN

A DISSERTATION SUBMITTED TO THE FACULTY
OF THE DIVISION OF THE PHYSICAL SCIENCES
IN CANDIDACY FOR THE DEGREE OF DOCTOR
OF PHILOSOPHY

DEPARTMENT OF GEOLOGY
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ABSTRACT

The structures of Archean granite and gneiss and overlying Lower Huronian sedimentary formations in the vicinity of Pine Creek in the northern part of the Menominee iron-bearing district of Michigan are compared in this study. Foliation of the gneiss is distinctly unconformable with bedding of the sediments. Faults, joints, and microstructures are similarly developed in the two rock types. During the Killarney orogeny these Archean and Lower Huronian rocks were upturned into a southwest-facing monocline, pushed back at its ends along northeast-trending tear faults. The petrofabrics of both the granitic and the sedimentary rocks plot into horizontal *A–C* girdles and are presumably the result of rotation about a vertical axis associated with the faulting.

INTRODUCTION

The Pine Creek area of southern Dickinson County, Michigan, constitutes the northern portion of the Menominee iron-bearing district. The area occupies a belt 16 miles long and 1–2 miles wide, which trends northwest, generally adjacent to the course of Pine Creek. Included in this belt is the southwestern margin of a complex of granites and gneisses and an almost continuous strip of strongly metamorphosed sedimentary rocks that flank the complex.

In 1904 W. S. Bayley[1] placed these sedimentary rocks in the Lower Huronian and cited occurrences of their basal conglomerates truncating foliation, pegmatite veins, and other structures of the granitic rocks of the Pine Creek area as conclusive evidence that the granites are of Archean age. His opinion remained undisputed in print until C. A. Lamey, discussing the possibility of an extension of the post-Huronian Republic granite, expressed doubt as to the age of the conglomerate and stated that the conglomerate proved "merely that some granite was exposed at the time of its formation, but does not prove the age of that granite or whether its occurrence was widespread or local."[2] F. J. Pettijohn[3] has recently restudied the basal conglomerate and has defended the view of Bayley.

This controversy supplied the impetus for the present study. It seemed probable that a detailed examination and a comparison of the structures, especially the petrofabrics, of the adjacent granitic and sedimentary rocks would give decisive information concerning the relative ages of the rock systems. The author, therefore, spent twelve weeks of the summer of 1946 in the Pine Creek area.

GENERAL GEOLOGY

The Archean complex is composed principally of pink gneisses and granites; subordinate to these are gray gneiss, migmatite, and brick-red granite. All phases of the complex are widespread except the red granite, which forms only 5 per cent of the complex and is restricted to small scattered patches in the northwestern part of the area.

[1] "The Menominee Iron-bearing District of Michigan," *U.S. Geol. Surv. Mono. 46* (1904).

[2] "Republic Granite or Basement Complex?" *Jour. Geol.*, Vol. XLV (1937), p. 507.

[3] "Basal Huronian Conglomerates of Menominee and Calumet Districts, Michigan," *Jour. Geol.*, Vol. LI (1943), pp. 387–97.

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The gneisses of the Archean complex are of primary igneous origin. Their folia are due to subparallel arrangement of layers of different composition. These folia vary locally in strike and dip; they wrap around xenoliths; and they wedge out and split into several bands. Much of the pink gneiss contains augen-like phenocrysts of potash feldspar, oriented parallel to the trends of folia, and in many outcrops this foliated pink gneiss grades imperceptibly into lineated pencil gneiss.

The upturned Lower Huronian sediments rest unconformably against the Archean complex. The basal part of the Lower Huronian series, termed the "Fern Creek formation" by F. J. Pettijohn,[4] is composed of 300 feet of conglomerate, arkose, graywacke, argillite, and phyllite. The conglomerate, which truncates structures of the Archean complex, was seen at the following localities: (1) at the falls of the Sturgeon River, Section 8, T. 39 N., R. 28 W.; (2) in the northwestern part of Section 8, T. 39 N., R. 28 W.; (3) at the falls of Black Creek, north-central part of Section 7, T. 39 N., R. 28 W.; (4) near Fern Creek, Section 34, T. 40 N., R. 29 W.; and (5) in the south-central part of Section 29, T. 41 N., R. 29 W.

Above the Fern Creek beds is the Sturgeon formation, which is divisible into a lower member of green sericitic quartzite and an upper member of white, vitreous, fine-grained quartzite. The average thickness of the Sturgeon formation is 1,000 feet. This formation grades into Randville dolomite, the upper member of the Lower Huronian system.

The youngest pre-Cambrian rocks of the area are a series of dikes and mineralized quartz veins, which intrude the Archean complex, and the Fern Creek and Sturgeon formations. The dikes are predominately metamorphosed gabbros and diabases, but in the northwestern part of the area occurrences of melasilexite and esmeraldite are noted.

[4] P. 397 of ftn. 3.

PRIMARY STRUCTURAL UNCONFORMITY

Although the existence of a major angular unconformity between the Archean complex and the Lower Huronian formations is proved by contacts of the basal conglomerates with the granitic rocks at well-spaced localities, this relationship is emphasized by comparing the general strike of the Sturgeon quartzite with the general trends of the foliation of the gneiss throughout the area.

The strike of the Sturgeon quartzite, consistently northwest, actually deviates between N. 15° W. and N. 85° W., and averages N. 50° W. In the eastern part of the Pine Creek area the foliation planes of the gneiss trend unvaryingly northwest and form an acute angle with the strike of the quartzite. West of Fern Creek, Section 34, T. 40 N., R. 29 W., the trends gradually change to north and even northeast, the angle between the foliation of the gneiss and the strike of the quartzite increasing to approximately 90°.

The discordance of trends of the quartzite and the gneisses is graphically illustrated by Figure 1, a diagram of the poles to bedding planes of the quartzite, and by Figures 2 and 3, diagrams of poles to foliation planes of the gneisses in the eastern and western parts of the area, respectively.

If the marginal granite gneisses were post-Huronian, their foliation, whether resulting from granitization of sediments or marking lines of flow of an intrusive massive, normally would conform to the general trend of the Lower Huronian rocks. Therefore, the hypothesis of post-

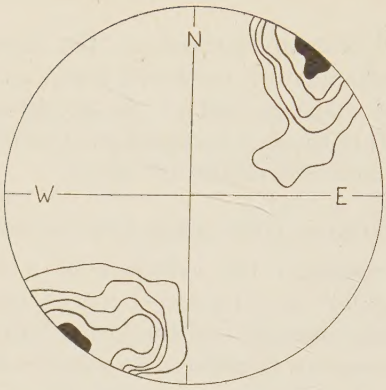


FIG. 1

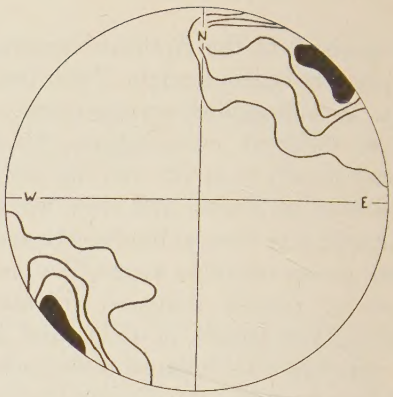


FIG. 2

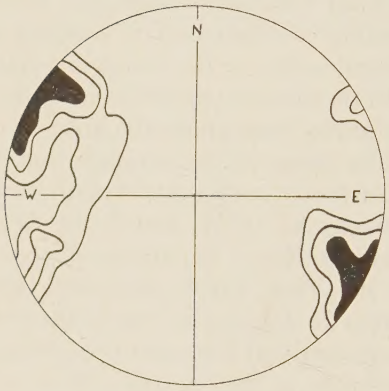


FIG. 3

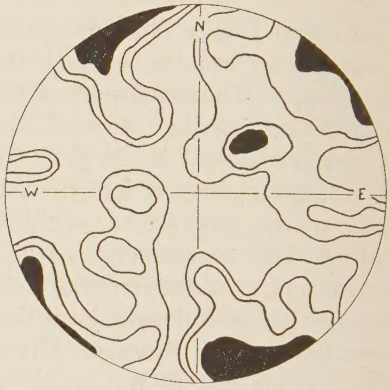


FIG. 4

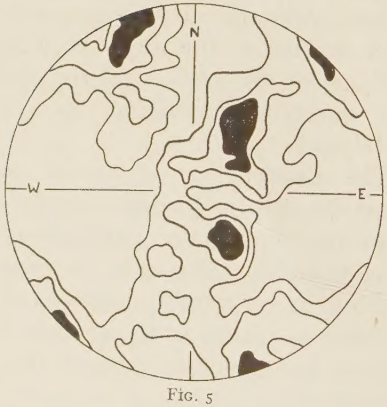


FIG. 5

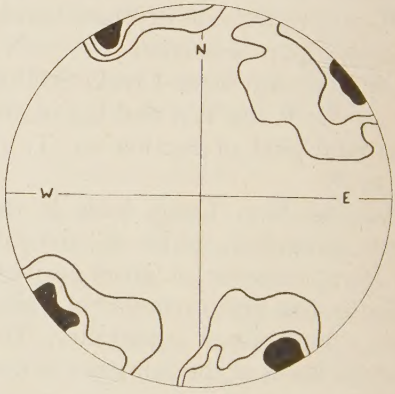


FIG. 6

FIGS. 1–6.—Fig. 1, poles of 119 bedding planes of quartzite west of Section 28, T. 40 N., R. 29 W. (20 per cent maximum). Fig. 2, poles of 50 foliation planes of gneiss east of Section 35, T. 40 N., R. 29 W. (12 per cent maximum). Fig. 3, poles of 70 foliation planes of gneiss west of Section 35, T. 40 N., R. 29 W. (10 per cent maximum). Fig. 4, poles of 76 joints of granitic rocks (4–7 per cent maxima). Fig. 5, poles of 301 joints of quartzite (4 per cent maxima). Fig. 6, poles of 36 joints of basic dikes (10 per cent maxima). All figures are plotted on the lower hemisphere of an equal-area net.

Huronian age of the granite complex is incompatible with the facts.

MAJOR DEFORMATIONAL STRUCTURES

The Lower Huronian strata of the Pine Creek area have been folded and subsequently faulted since their deposition. Both folding and faulting probably were separate phases of the Killarney orogeny.

During the folding the rocks were upturned into a monocline that faced southwest. Dislocated remnants of this monocline are preserved as bluffs of Sturgeon quartzite, which form an arc trending northwest from the center of Section 9, T. 39 N., R. 28 W., to the southwest corner of Section 20, T. 41 N., R. 29 W. The convexity of this line of bluffs is not due to progressive change of strike of the quartzite, however, but to progressive displacement of the quartzite along northeast-trending vertical faults.

The strike of the quartzite, as stated in an earlier paragraph, deviates between N. 15° W. and N. 85° W. and is generally N. 50° W. (Fig. 1). The deviations are local and sporadic and are caused by contortion and rotation of faulted blocks. The dip of the quartzite also has been markedly affected by fault-block rotation. Where faulting is not conspicuous, the beds are vertical or dip steeply southwest. At many places where faulting has been forceful, the beds are overturned and dip northeast, evidently the consequence of tilting of faulted blocks. However, some of the overturning may be the result of underthrusting of quartzite during folding.

Faults of the Pine Creek area are of the tear type. Twenty-one of these faults can be safely inferred and are shown on the structure map, but other faults of inappreciable displacement may exist. Fifteen of these faults are concentrated in the northwestern Pine Creek area. All fifteen strike northeast, their average trend being N. 58° E. Along eleven of the faults the northwest blocks have been displaced northeast through an aggregate distance of more than 3.5 miles. A relatively southwest displacement of northwest blocks along the other four faults totals approximately 1,100 feet.

If the displacements along the fifteen faults are added vectorally and the resultant resolved into east-west and north-south components, the total displacement is 3.5 miles in a direction N. 70° E., the east-west component is 3.2 miles, and the north-south component is 1.2 miles (Fig. 7). The fact that the east-west component has nearly three times the magnitude of the north-south component implies that the forces of faulting were essentially directed from the west.

Related to the faulting of the northwestern area are shear zones strongly developed in both the quartzite and the granite. The rocks in these zones are brecciated or cleaved along closely spaced planes. Some of the zones are found in the immediate vicinities of mappable faults. However, many occur at considerable distances from definite faults, but may themselves be minor faults along which displacement is not prominent.

All except three of seventeen observed shear zones of the quartzite trend between N. 55° E. and east-west. The average trend of all the zones is N. 67° E., differing from the average strike of the faults (N. 58° E.) by only 9° and from the trend of the resultant of the fault movements (N. 70° E.) by only 3°. In several instances shear planes are strongly striated. The pitch of these striations ranges from nearly horizontal (2° NE.) to 40° SW. The pitch of the striations and the average strike of the shear zones

are evidence that the general shear movement was upward at a low angle from west of southwest.

The trends of nineteen observed shear zones in the granite range between N. 15° E. and east-west, and average N. 52° E. This latter figure differs from the average trend of the faults by only 6° and from the average trend of the shear zones in the quartzite by 15°.

Brick-red granite, the only phase of the granitic complex which is nowhere truncated by Lower Huronian basal conglomerate, is intensely sheared in several outcrops. Thus this granite is proved to be older than the faulting, although not necessarily Archean.

At the southeastern end of the Pine Creek area three faults have been mapped. These faults have strikes of N. 44° E., N. 45° E., and N. 60° E., and horizontal displacements of 300, 100, and 100 feet, respectively. In each instance the southeast block has been displaced northeast, the relative movement being opposite to that in the northwestern part of the area.

The central part of the area is but slightly faulted, only three small northeast-trending faults in the vicinity of Fern Creek, Section 34, T. 40 N., R. 29 W., being observed in a distance of 7 miles. Moreover, the quartzite of this area is characteristically sheared parallel to bedding planes. In some outcrops the long dimensions of autoclasts of quartzite are oriented subparallel to the strike of the beds. Therefore, it is assumed that the shearing has resulted from lateral, rather than from vertical, slippage of the bedding planes.

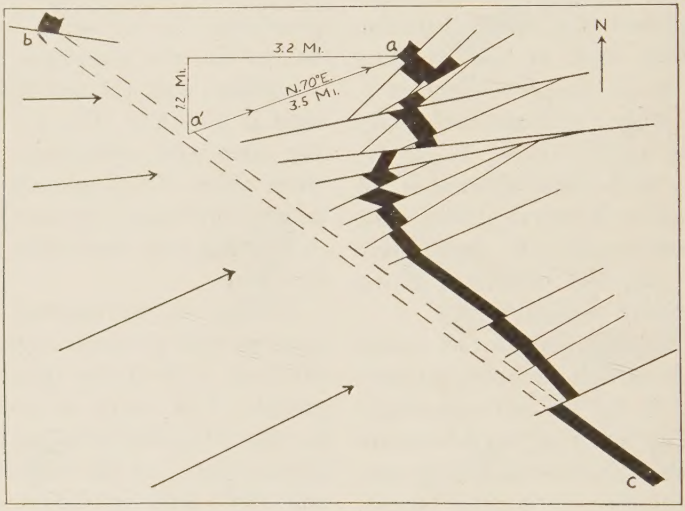


FIG. 7

The faults of the Pine Creek area are not local phenomena but are elements of a regional system. C. E. Dutton and C. A. Lamey have found similar faults in parts of the Menominee iron-bearing district which lie several miles south of the granitic complex. They write:

> Likewise, Although it is recognized that folding is an important factor in the regional distribution of formations, faulting evidently dominates their local distribution. Furthermore, a systematic orientation of faults is apparent, and a well-defined fault pattern comprising (1) a conspicuous set of faults with northeast-south-

west trends, and (2) less conspicuous sets trending (*a*) northwest-southeast, (*b*) nearly north-south, and (*c*) approximately east-west.[5]

The concentration of faults in the northwestern and southeastern parts of the Pine Creek area and the characteristic development of bedding-plane shear in the least faulted central part of the area are best explained by assuming that the Pine Creek monoclinal structure was reinforced by the massive complex of Archean granite. Forces pushing from the southwest against the buttressed central part of the monocline were deflected parallel to the monoclinal front. Although these forces were unable to fault the unyielding granite massive at its center, their deflection was accompanied by lateral slippage of the less competent quartzite along bedding planes. On the other hand, the same forces faulted and pushed back the monoclinal structure at its least resistant ends. The total movement is analogous to that of the front of a glacier thrusting against and moving around a nunatak.

If successive fault blocks in the northwestern part of the Pine Creek area are moved back along their planes, beginning with the fault of Section 20, T. 40 N., R. 29 W., distances equal to their displacements, an approximation of the original front of the Pine Creek monocline can be obtained. The northwesternmost outcrop of quartzite now in the southwest corner of Section 20, T. 41 N., R. 29 W., is moved to a position in the northwest corner of Section 35, T. 41 N., R. 30 W. The same position is obtained if the northwesternmost outcrop is moved a distance equal to, and in a direction opposite to, its total displacement, that is, 3.5 miles in the direction S. 70° W. This position is on the projected strike (N. 53° W.) of unfaulted quartzite, which crops out in Section 28, T. 40 N., R. 29 W., and is less than 3 miles from Sturgeon quartzite near Browning Creek, Section 20, T. 41 N., R. 30 W., which has been described by Pettijohn.[6]

These relationships are pictured in Figure 7. The present and reconstructed positions of the northwesternmost outcrop of quartzite in the Pine Creek area are represented by *a* and *a'*, respectively. The quartzite at Browning Creek is *b*, and the unfaulted quartzite is *c*.

Although the present distance between the Pine Creek and Browning Creek exposures of quartzite is about 6 miles, it is thought that, before faulting, the quartzites at these localities were connected parts of the Pine Creek monocline. This monocline evidently curved northward in the vicinity of Browning Creek, because Pettijohn has determined the average strike of the quartzite at that locality to be N. 35° E.[7]

Two structural features of the Archean complex have resulted from the deformation during the folding of the Pine Creek monocline. The first of these is boudinage structure, occurring in several outcrops in the northwestern part of the area, where lenses of granitic material, 6 inches to 3 feet thick, have been injected into what are now biotite-hornblende schists. These competent lenses dip toward the quartzite and have been broken along their dips into links or boudins surrounded by the more plastic schists. The development of these boudinage structures is attributed to stretching of the granitic lenses as they yielded to forces which folded the quartzite.

A second evidence of deformation of the Archean gneiss is a thrust fault zone

[5] "Geology of the Menominee Range Vicinity of Iron Mountain," *Mich. Dept. Conserv., Geol. Surv. Div. Prog. Rept. 6* (1941), p. 3.

[6] Pp. 395–97 of ftn. 3.

[7] *Ibid.*, p. 395.

in the eastern part of the area. This zone, about $\frac{1}{4}$ mile north of the margin of the complex, is marked by a sharp reversal in dip of foliation planes of the gneiss and is traceable from Section 9, T. 39 N., R. 28 W., to Section 27, T. 40 N., R. 29 W., a distance of 6 miles (see Map I). Folia of the gneisses in outcrops south of this zone strike unvaryingly northwest and dip southwest, whereas the folia in outcrops north of the zone also strike consistently northwest but dip northeast. Furthermore, northwest strike and northeast dip are characteristic of gneisses throughout the width of the complex north of this zone of dip reversal. Because the northwestern part of the Pine Creek area is so complexly faulted, no integrated zone of dip reversal could be determined there.

Inasmuch as the southwest-dipping gneisses of the margin of the complex, that is, south of the zone of dip reversal, are in direct contact with, and truncated by, the basal conglomerate of the sedimentary series, it is evident that the gneisses at these contacts have been upturned through the same angular distance as the sedimentary rocks. Therefore, the attitudes of the gneisses before deposition of the sediments can be obtained simply by solving the "two-tilt" problem on the stereographic net.[8] This solution involves merely the rotation of a particular plane of foliation about an axis corresponding to the strike of adjacent quartzite and through an angle of such magnitude that the quartzite becomes horizontal.

Folia of gneisses of ten well-spaced outcrops adjacent to quartzite have been rotated in this manner, and their resulting attitudes have been plotted on a map (Fig. 8). To this map have been added typical attitudes of nonrotated folia north of the zone of dip reversal. Finally, the approximate original locations of all folia have been obtained by reconstructing the faulted blocks. The result is a concatenated pattern suggestive of a pluton, the center of which probably was near Fern Creek, Section 34, T. 40 N., R. 29 W., where trends of the foliation change from northwest to northeast.

Therefore, an assumption that the marginal gneisses originally had trends similar to those obtained by rotation, but were subsequently overturned, probably during the formation of the Pine Creek monocline, is indeed credible. Inasmuch as the zone which separates the overturned and nonfolded gneisses is so sharply delimited, it may reasonably be considered a fault zone. This fault probably formed along the axial plane of the monocline and most likely was developed by thrust from the northeast. Such thrusting would have helped to overturn the marginal gneisses.

JOINTING

Similar systems of joints in the granite gneisses and the Sturgeon quartzite are considered evidence that the Archean and Lower Huronian rocks have the same deformational history. The similarity of the joint systems of these rocks is demonstrated by Figures 4 and 5.

One system of joints in the granite consists of a set that strikes N. 45° W. and dips 45° SW., and a weaker set that strikes N. 45° W. and dips about 40° NE. A system of joints in the quartzite includes a set which strikes northwest and dips 45° SW., and a set which strikes northeast and dips 30° NW. If these joints in the granite and quartzite are assumed to be compressional, the bisector of the acute angle of the two sets in

[8] W. H. Bucher, "The Stereographic Projection: A Handy Tool for the Practical Geologist," *Jour. Geol.*, Vol. LII (1944), pp. 203–4.

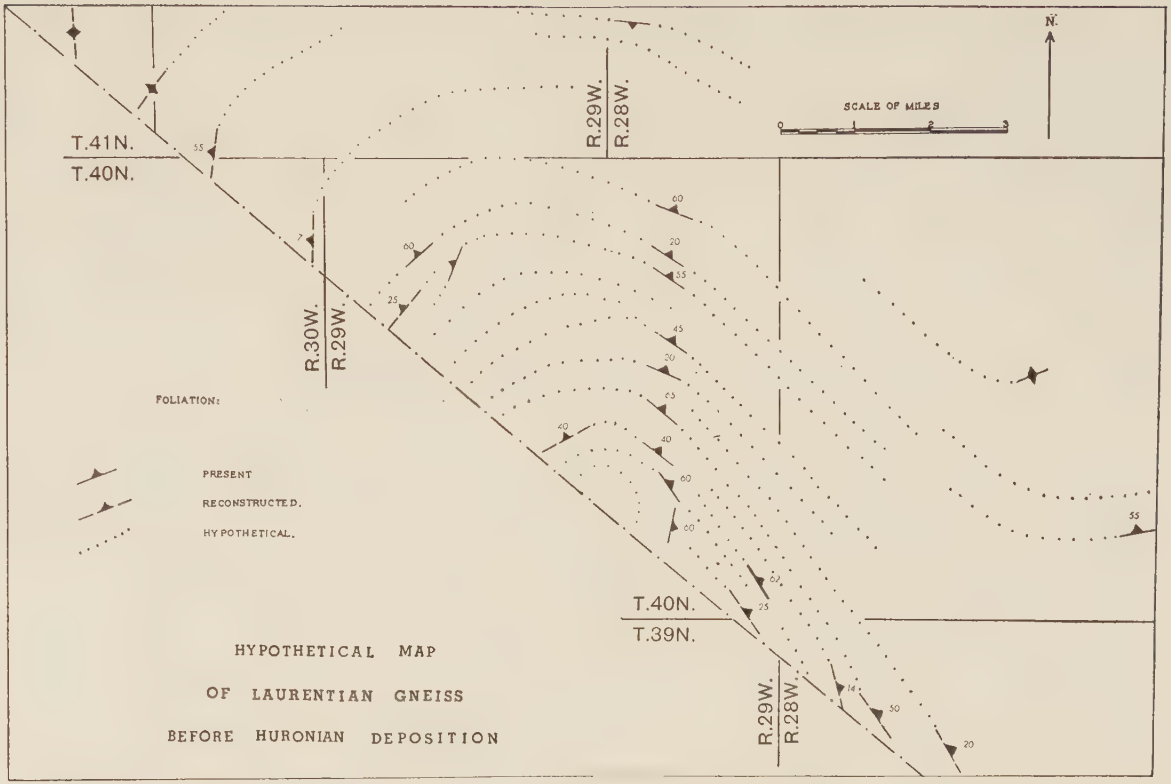

N.
SCALE OF MILES
0 1 2 3
T.41N.
T.40N.
T.40N.
T.39N.
R.30W.
R.29W.
R.29W.
R.28W.
R.29W.
R.28W.
FOLIATION:
PRESENT
RECONSTRUCTED.
HYPOTHETICAL.
HYPOTHETICAL MAP
OF LAURENTIAN GNEISS
BEFORE HURONIAN DEPOSITION

FIG. 8

each rock type is equal to the direction of maximum compression. This direction, obtained by use of the stereographic net as outlined by W. H. Bucher,[9] is 15° upward from S. 10°W. if determined by the joints in the quartzite and is nearly horizontal from S. 40° W. if determined by joints in the granite. These directions correspond closely enough to postulate that the conjugate sets of joints of low-angled dip in the quartzite and granite probably resulted from the same forces of deformation. The general direction of the compression which produced these systems of joints is approximately perpendicular to the trend of the Pine Creek monocline. Therefore, the joints may have formed during the folding of this monocline.

A second system of joints, consisting of two vertical sets which trend north-east and northwest, is also equally present in both the granite and the quartzite. The northeast-trending joints, the most conspicuous of the Pine Creek area, locally are the controlling factors of topography. The northwest-trending joints have an average attitude similar to that of the bedding of the quartzite, and many bedding planes are separated by these joints. However, in localities where the bedding differs in strike and dip from the average, these northwest-trending vertical joints are quite distinct from bedding planes.

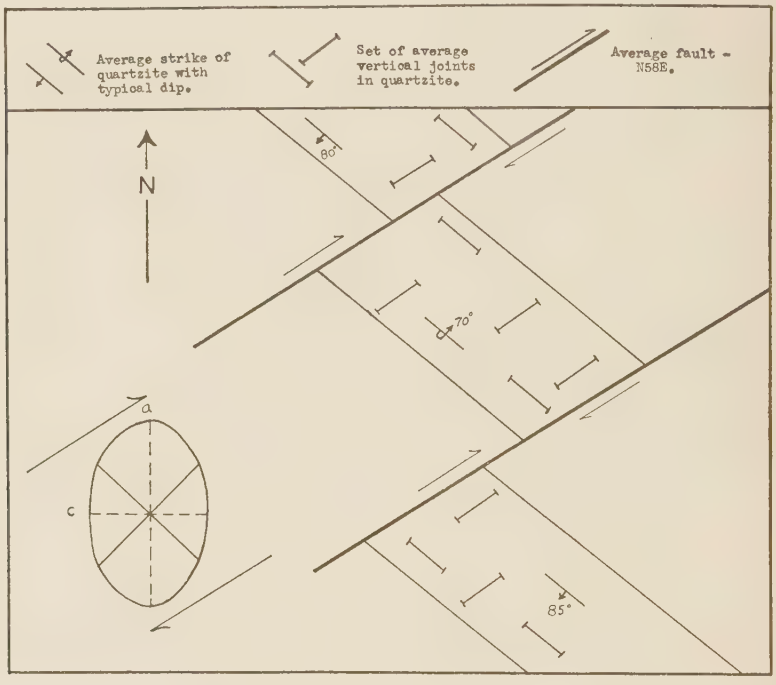


FIG. 9

Both sets of the vertical joints are particularly well shown near zones of faulting, especially in the northwestern part of the area. They may be shear joints related to a couple produced by differential movement of the fault blocks. Figure 9 discloses the possible relationship of these joints to the faulting in the north-

[9] *Ibid.*, p. 196.

western part of the area and to the strain ellipsoid. The strain ellipsoid of the figure indicates that the couple produced an effective component of elongation (*a*) in a north-south direction, and one of compression (*c*) in an east-west direction. The directions of these components of force agree with those obtained by an earlier vectoral analysis of the fault movements of the northwestern area.

The joints of post-Huronian basic dikes of the Pine Creek area belong to a system of vertical sets which correspond in strike to the vertical sets of the granite and quartzite (Fig. 6). Apparently, therefore, the joints of the basic dikes were produced during the faulting. On the other hand, the absence in the dikes of the sets of low-angled joints, common to both the quartzite and the granite gneiss and supposedly related to the folding, is evidence that the dike rocks were intruded either during final stages of the folding or later. Thus the rocks of the granitic complex are not only clearly divorced from, but also definitely older than, the only major features of post-Huronian igneous intrusion. This fact emphasizes the probability of Archean age of this complex.

PETROFABRICS

To supplement the structural data obtained in the field, a petrofabric study has been made of eight samples of the granite and twelve samples of the quartzite. The positions of these samples relative to major structures can be found on the structure map (Map I). The samples of granite and gneiss are designated by the letters A through H, and the quartzite by numerals 1 through 12.

It is not considered necessary to give an elaborate discussion of the theory and procedures of petrofabric analysis. These subjects are treated thoroughly in books by Bruno Sander,[10] Eleanor Knopf and Earl Ingerson,[11] H. W. Fairbairn,[12] M. P. Billings,[13] R. C. Emmons,[14] and in excellent papers by Anna Hietanen[15] and by R. E. Fellows.[16]

METHODS

All samples were oriented in the field relative to some *S*-plane of determined strike and dip, usually a bedding or foliation plane, less frequently a shear plane. Two sections of each specimen were cut for study, one perpendicular to the strike and parallel to the dip of an *S*-plane, the other at right angles to the first, perpendicular to the dip and parallel to the strike.

A study was made of the orientation of the *c*-axes of 200–300 quartz grains in each thin section. For this study a petrographic microscope of the Leitz type and a 4-axis Universal Stage were used. The size of the quartz grains in all samples ranges from less than 0.05 mm. in crush-quartz to more than 1.0 mm. in original grains. Only larger grains were chosen for measurement, as the importance of discrimination in grain selection is becoming increasingly recognized.[17] However, all

[10] *Gefügekunde der Gesteine* (Vienna: Julius Springer, 1930).

[11] "Structural Petrology," *Geol. Soc. Amer. Mem. 6* (1938).

[12] *Structural Petrology of Deformed Rocks* (Cambridge: Addison-Wesley Press, Inc., 1942).

[13] *Structural Geology* (New York: Prentice-Hall, Inc., 1942), pp. 352–55.

[14] "The Universal Stage," *Geol. Soc. Amer. Mem. 8* (1943).

[15] *On the Petrology of Finnish Quartzites* (Helsinki: Government Press, 1938).

[16] "Recrystallization and Flowage in Appalachian Quartzite," *Bull. Geol. Soc. Amer.*, Vol. LIV (1943), pp. 1399–1432.

[17] *Ibid.*, p. 1422; also "The Influence of Grain-Selection on the Meaning of Quartz Diagrams," *Amer. Geophys. Union Trans.* (1945), pp. 653–59.

the large grains were selected at random along five or six well-spaced traverses across the slide. Two of the diagrams are more selective than the others because only those grains showing some degree of undulatory extinction were chosen.

To insure the existence of homogeneity, the grains were plotted in separate groups of 50 or 100, and an inspection made for the tendencies of concentration after each group had been plotted. The plotting was done on the lower hemisphere of an equal-area net of the so-called "Schmidt" type. Concentrations of the *c*-axes were determined by standard center and peripheral counters of 1.0-cm. radius. Counting was spaced by grid distances of 1.0 cm. This was supplemented by closer counting in areas of maxima.

The diagrams which have resulted from the study of sections cut perpendicular to *S*-planes have been rotated into a horizontal plane and are plotted on the structure map. The procedure of rotation of these diagrams was that outlined by Ingerson.[18]

OBSERVATIONS AND INTERPRETATION

The most apparent feature of the fabric diagrams is that they all have peripheral maxima. On the basis of position of the peripheral maxima, the diagrams may be divided into three types.

One type of diagram is characterized by maxima lying between east-west and northeast-southwest, being transverse to any primary structures of the rocks. Diagrams of this type are restricted to samples collected from the southeastern Pine Creek area.

A second distinct type is most common to samples of the northwestern part of the area. Maxima of this type have positions generally north-south. The orientations of these maxima are transverse to bedding planes of the quartzite but usually subparallel to foliation of the gneiss.

To a third type belong a remaining few diagrams of quartzite. The maxima of this type have positions subparallel to bedding planes of the quartzite and may be related merely to residual sedimentary fabric, but more probably to bedding-plane shear. The diagrams of Samples 3, 4, and 5 of the quartzite belong to this type.

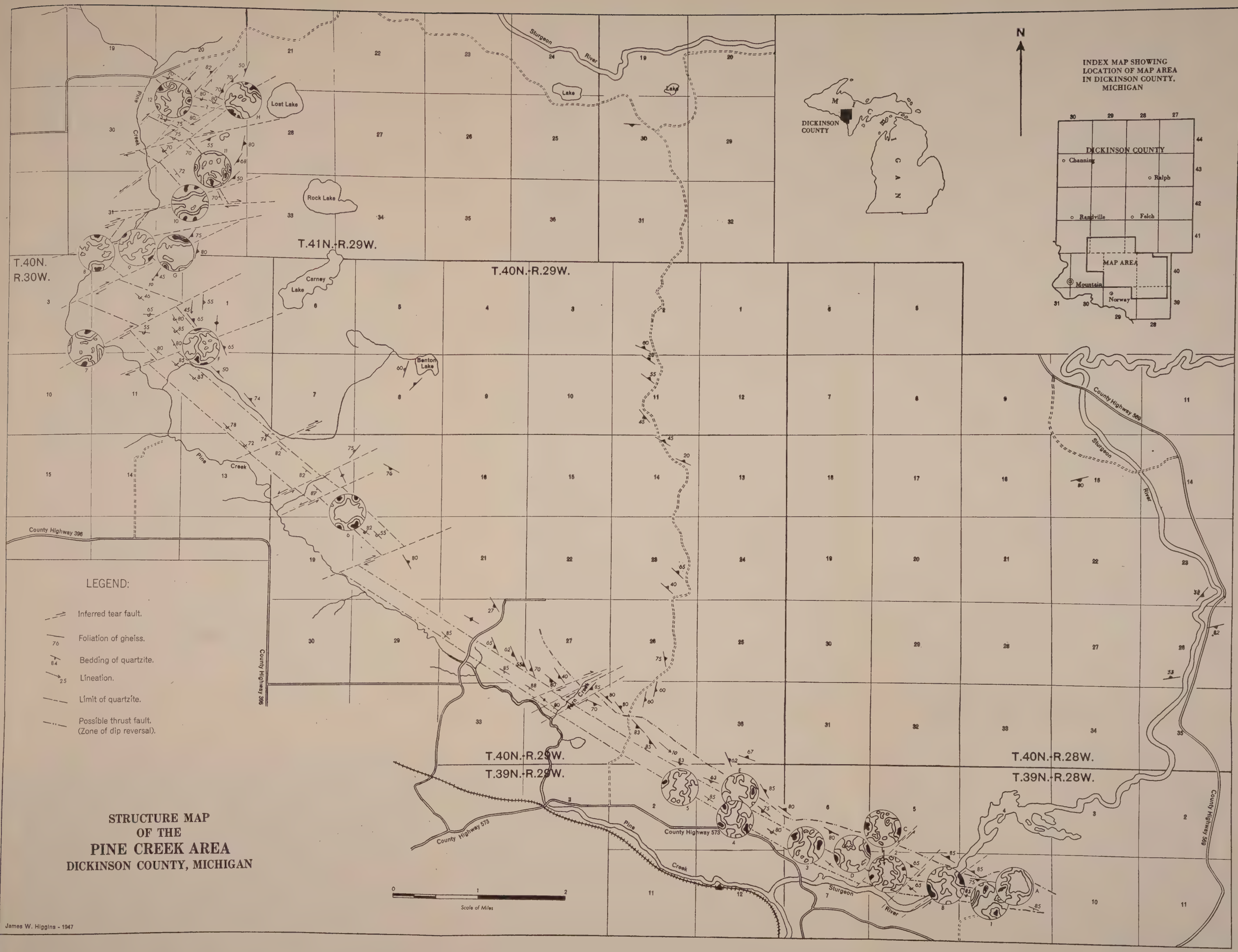
Many of the maxima of the diagrams are point maxima, but a few, such as those of Samples 2, 4, and 6 of the sedimentary rocks and Samples A and E of the granite, belong to horizontal girdles. If these horizontal girdles are *A–C* girdles, the directed force must have acted in a nearly horizontal plane about a vertical axis of rotation. Such a force was associated with the faulting. Therefore, a comparison of the fabrics and the faults is desirable.

In order to ascertain just how closely the fabrics of the rocks are related to the faulting, two composite diagrams have been made of samples of the faulted southeastern and northwestern areas. The true value of composite diagrams has been pointed out by F. C. Phillips, who states: "These diagrams, it may be noted, summarize facts of observation. Any conclusions which may be derived from them are unaffected by any of the theoretical considerations of structural petrology."[19]

One diagram (Fig. 10) is constructed from 2,600 grains of Samples 1–5 of the quartzite and Samples A–E of the gneiss. The second diagram (Fig. 11) represents 1,950 grains of Samples 7–12 of the quartzite and Samples F–H of the gran-

[18] Pp. 257–62 of ftn. 11.

[19] "The Micro-fabric of the Moine Schists," *Geol. Mag.*, Vol. LXXXII (1945), p. 206.



STRUCTURE MAP OF THE PINE CREEK AREA DICKINSON COUNTY, MICHIGAN

Sample

1. . . .300 grains of quartz in quartzite (3 per cent maxima)
2. . . .200 grains of quartz in graywacke (4 per cent maximum)
3. . . .300 grains of quartz in quartzite (4–5 per cent maxima)
4. . . .300 grains of quartz in quartzite (3 per cent maxima)
5. . . .300 grains of quartz in quartzite (4 per cent maximum)
6. . . .300 grains of quartz in quartzite (4–5 per cent maxima)
7. . . .250 grains of quartz in quartzite (4–8 per cent maximum)

Key to Fabric Diagrams on Structure Map

Sample

8. . . .200 strained grains of quartz in quartzite (4–9 per cent maximum)
9. . . .200 grains of quartz in quartzite (4 per cent maximum)
10. . . .250 grains of quartz in quartzite (4 per cent maxima)
11. . . .250 grains of quartz in green sericitic quartzite (3 per cent maxima)
12. . . .200 grains of quartz in quartzite (4–6 per cent maxima)
A. . . .300 grains of quartz in pink gneiss (4 per cent maximum)
B. . . .200 grains of quartz in pink gneiss (4–6 per cent maximum)

Sample

C. . . .250 grains of quartz in pink gneiss (4 per cent maximum)
D. . . .250 grains of quartz in gray gneiss (4–5 per cent maximum)
E. . . .200 grains of quartz in pink gneiss (4–5 per cent maximum)
F. . . .200 grains of quartz in gray gneiss (4–6 per cent maxima)
G. . . .200 grains of quartz in brick red granite (4–8 per cent maximum)
H. . . .200 undulatory quartz grains in pink gneiss (4–7 per cent maxima)

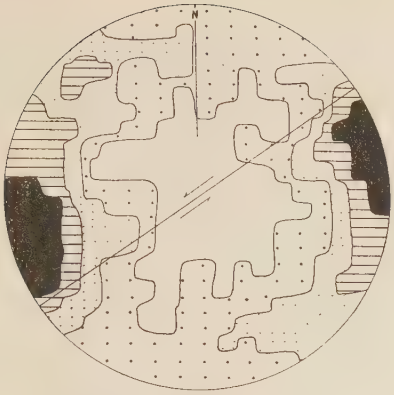


FIG. 10

FIG. 11

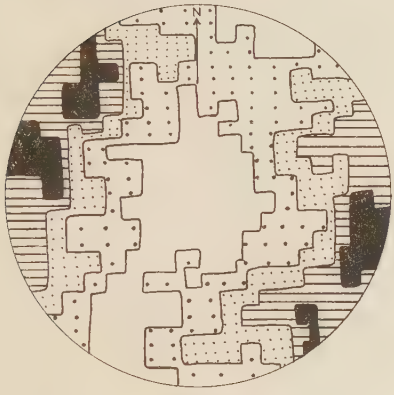


FIG. 12

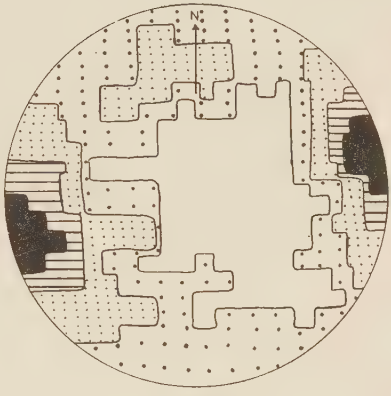


FIG. 13

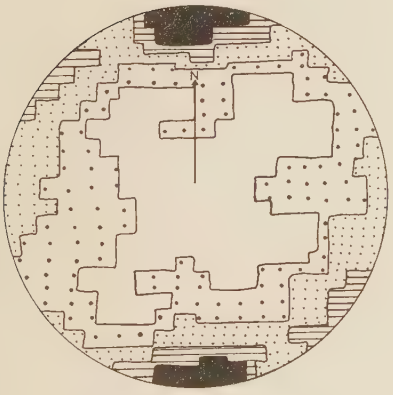


FIG. 14

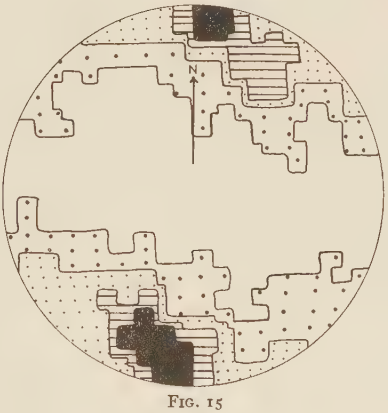


FIG. 15

FIGS. 10–15.—Fig. 10, composite diagram of 2,600 quartz grains of Samples 1–5 and A–E ($\frac{1}{2}$, 1, $1\frac{1}{2}$, $2–2\frac{1}{2}$ per cent). Southeastern part of Pine Creek area. Fig. 11, composite diagram of 1,950 quartz grains of Samples 7–12 and F–H ($\frac{1}{2}$, 1, 2, 3 per cent). Northwestern part of Pine Creek area. Fig. 12, composite diagram of 1,400 quartz grains of Samples 1–5 of quartzite ($\frac{1}{2}$, 1, $1\frac{1}{2}$, 2 per cent). Southeastern part of Pine Creek area. Fig. 13, composite diagram of 1,200 quartz grains of Samples A–E of gneisses ($\frac{1}{2}$, 1, 2, 3 per cent). Southeastern part of Pine Creek area. Fig. 14, composite diagram of 1,350 quartz grains of Samples 7–12 of quartzite ($\frac{1}{2}$, 1, 2, 3 per cent). Northwestern part of Pine Creek area. Fig. 15, composite diagram of 600 quartz grains of Samples F–H of granite and gneiss ($\frac{1}{2}$, 2, 3, 4 per cent). Northwestern part of Pine Creek area.

ite and gneiss. The average trends of the faults of the areas have been superposed on the diagrams.

The diagram of Figure 10 is a girdle. A peripheral maximum of 2–2½ per cent indicates that a large number of the *c*-axes of the grains are oriented slightly north of east, 25° more to the east than is the average strike of the faults. From the arrows which indicate relative direction of movement of fault blocks, it can be seen that the maximum orientation of the *c*-axes corresponds very well to the direction of elongation of a strain ellipsoid acted upon by a shear couple. The small 1½ per cent submaximum in the northwest quadrant of Figure 10 is possibly due to lateral yielding, through bedding-plane shear, perpendicular to a force from the southwest.

Figure 11 shows that preferred orientation, represented by a 3 per cent peripheral maximum, is north-south. This orientation corresponds to the axis of elongation of a strain ellipsoid acted upon by a couple produced by faulting (Fig. 9); therefore, the maxima are assigned to an *a*-tectonic axis. Fairbairn has cited the development of *a*-maxima in slickensides and states that they "may therefore be considered parallel to the direction of movement."[20] Diagrams of Samples B and H, collected in fault zones, prove the validity of Fairbairn's statement. In the immediate vicinity of the faults the *a*-axis of the strain ellipsoid is tangential to the fault plane. However, it is postulated that, with increasingly greater distances from the fault zone, the *a*-axis of the strain ellipsoid becomes acutely inclined to the strike of the fault. Because most of the rocks studied are located within fault blocks at considerable distances from any fault plane, the maxima of the composite diagrams are developed acutely to the average strike of the faults.

In order to determine whether the fabrics of quartzite are distinctly similar or dissimilar to those of the granitic rocks, separate composite diagrams have been made of the samples of each of these rock types in both the southeastern and the northwestern areas.

The diagrams of the quartzite (Fig. 12) and of the granite (Fig. 13) in the southeastern area are distinctly similar, in that both are girdles with general orientation of quartz axes east-west. A minor difference is that the quartzite diagram has two peripheral maxima, a large one oriented slightly south of east and a smaller one oriented northwest, subparallel to bedding, whereas the diagram of the granitic rocks has but one large peripheral maximum, oriented a few degrees north of east. Preferred orientation subparallel to bedding of the quartzite most likely resulted from bedding-plane shear.

The composite diagrams of samples of the quartzite (Fig. 14) and of samples of granite and gneiss (Fig. 15) of the northwestern Pine Creek area have identical maxima. The only difference between these diagrams is that the maximum of the quartzite diagram is part of a girdle, whereas that of the diagram of the granitic samples is a point maximum.

In summary, it can be stated that the microstructures of rocks of the Pine Creek area are tectonic. Furthermore, all specimens studied have fabrics produced by deformation involving a vertical rather than a horizontal *B*-tectonic axis. Inasmuch as the folding of the Pine Creek area was about a horizontal *B*-axis and the faulting was about a vertical *B*-axis, the rock fabrics are related to the faulting. The general similarity of composite diagrams is adequate proof that

[20] P. 9 of ftn. 12.

the forces involved left the same imprint on both the sedimentary and the granitic rocks.

SUMMARY

Evidences of structure presented in this report are in accord with earlier statements of Bayley and Pettijohn that the complex of granites and gneisses in the Pine Creek area is of Archean age. Trends of foliation of the Archean gneisses are definitely unconformable with the general strike of adjacent upturned Lower Huronian sedimentary rocks. The faults and joints, as well as the microscopic structures of the granitic and sedimentary rocks, are identical.

Also it has been shown that the strata of the Pine Creek area have been deformed at least twice since Archean time, though both deformations probably were separate phases of the Killarney orogeny. During the first phase the Huronian sediments and underlying Archean rocks were folded into a northwest-trending monocline that probably was thrust-faulted along its axial plane. During the second phase of deformation this structure was displaced at its northwestern and southeastern ends by vertical tear faults that trend northeast. The aggregate displacement along faults at the northwestern end has been approximately 3.5 miles. The movement at the southeastern end of the structure was of less magnitude than, and of opposite direction to, that at the northwestern end. The central part of the Pine Creek area was faulted only slightly, but quartzite in this area has been sheared parallel to bedding planes. It is postulated that the faulting and bedding-plane shear have resulted from forces directed from the southwest against the monoclinal structure. These forces were deflected laterally along the central front of the monocline, reinforced by the massive Archean buttress, but were able to displace the monocline at its least resistant ends.

Rock fabrics attest the severity of the fault deformation. The orientation of the *c*-axes of quartz grains in both granitic and sedimentary rocks which crop out in the faulted areas are related to rotational shear about a vertical axis. This shear has been correlated with differential movement of adjacent fault blocks, the components of any one block necessarily being acted upon by a couple.

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